

Consensus Statement

New trends in active faulting studies for seismic hazard assessment (*)

Enzo Boschi⁽¹⁾, Domenico Giardini⁽¹⁾, Daniela Pantosti⁽¹⁾, Gianluca Valensise⁽¹⁾,
Ramon Arrowsmith⁽²⁾, Peter Basham⁽³⁾, Roland Bürgmann⁽⁴⁾, Anthony J. Crone⁽⁵⁾, Alan Hull⁽⁶⁾,
Robin K. McGuire⁽⁷⁾, David Schwartz⁽⁸⁾, Kerry Sieh⁽⁹⁾, Steven N. Ward⁽¹⁰⁾ and Robert S. Yeats⁽¹¹⁾

⁽¹⁾ *Istituto Nazionale di Geofisica, Roma, Italy*

⁽²⁾ *Arizona State University, Tempe, AZ 85287-1404, U.S.A.*

⁽³⁾ *Geological Survey of Canada, Geophysics Division, Ottawa, ON K1A0Y3, Canada*

⁽⁴⁾ *University of California, Davis, CA 95616, U.S.A.*

⁽⁵⁾ *USGS, Branch of Geologic Risk Assessment, Denver, CO 80225-0046, U.S.A.*

⁽⁶⁾ *Institute of Geological and Nuclear Science, Lower Hutt, New Zealand*

⁽⁷⁾ *Risk Engineering Inc., Golden, CO 80403, U.S.A.*

⁽⁸⁾ *USGS, Menlo Park, CA 94025, U.S.A.*

⁽⁹⁾ *Geological and Planetary Sciences 170-25, CALTECH, Pasadena, CA 91125, U.S.A.*

⁽¹⁰⁾ *Earth Sciences Board, UCSC, Santa Cruz, CA 95064, U.S.A.*

⁽¹¹⁾ *Department of Geosciences, Oregon State University, Corvallis, OR 97331-5506, U.S.A.*

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ened by the construction of seismically unsafe buildings and infrastructures.

1. Introduction

Vulnerability to earthquakes increases steadily as urbanization and development expand in areas that are prone to the effects of significant earthquakes. As virtually all of the largest earthquakes of the past decade demonstrated, the development of large cities in high seismicity areas is often based on an insufficient knowledge or distorted perception of the local seismic hazard, a condition often wors-

2. Seismic Hazard Assessment (SHA)

The seismic hazard is a measure of the threat of earthquake ground shaking and is defined as the probability of occurrence of a certain level of shaking in a specified time interval at a given location. A map of seismic hazard contours levels of hazard expressed in terms of ground shaking parameters such as intensity, peak ground acceleration or spectral characteristics. The assessment of seismic hazard is the first step in the evaluation of seismic risk, obtained by convoluting the seismic hazard with local site amplification effects related to soil conditions and with the intrinsic value and vulnerability of the existing buildings and infrastructures. Frequent, large events in remote areas result in high seismic hazard but

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Mailing address: pantosti@ingrm.it; valensise@ingrm.it

pose little or no risk; on the contrary, moderate events in densely populated areas entail small hazard but may constitute a high risk. A seismic hazard map is the basic input for a comprehensive strategy of seismic risk mitigation, including the adoption of national seismic zoning and of safe building construction codes, the protection of critical facilities and of the cultural heritage, the planning of land use management and of disaster preparedness.

The assessment of seismic hazard depends upon our understanding of how earthquakes are generated and distributed and of how they recur in space and time. Three approaches are commonly used in probabilistic SHA at regional scale. The *historical* method attempts to reproduce the patterns of historical seismicity (location in space and time, frequency-size distribution) by a statistical model of the seismogenic sources. The *seismotectonic* approach incorporates geological and geophysical evidence to supplement the historical record of seismicity. The fundamental level uses geodynamic information to identify potential source areas and to delineate regions of comparable tectonic activity over which all available information can be averaged. More advanced approaches incorporate fault locations and rates, by gauging crustal deformation through geomorphology and space geodesy, and average recurrence intervals by analyzing records of individual paleoearthquakes. The *time-dependent* approach utilizes non-Poissonian statistics to incorporate the memory of past events in the probabilistic scheme, so that fault zones that ruptured in recent large earthquakes become less hazardous than others that did not rupture in recent history.

The historical approach works well only in plate boundary areas characterized by frequent occurrence of large earthquakes and «reasonable» completeness of the historical record. Recourse to geological input (implied in the remaining approaches) is inevitable in all cases of incomplete historical record and always in areas of diffuse deformation or slowly interacting plate boundaries, where large earthquakes may recur every 10^3 - 10^5 years.

Unfortunately, using one or the other approach leads to widely different expectations

of short-term hazard in the common case of incomplete historical record; the choice of methodology is dictated by the quality and completeness of the available data but usually also by the specific needs and applications of the SHA products at national level. The historical record of earthquakes in Europe and Asia has often been regarded as a sound basis from which to evaluate seismic hazard; however, the incompleteness of the historical record over large time gaps and its inability to define the earthquake source zones accurately is leading SHA experts to seek more geological input for their models. Much of the Pacific margin, on the contrary, lacks a long historical record and has traditionally relied on geology to avoid producing bull's eye maps dominated by few seismic sequences. The lack of coordination across boundaries is also a factor of large uncertainty, resulting in widespread inconsistencies in fragmented areas such as the Mediterranean basin. The seismotectonic probabilistic approach to SHA remains the method most commonly used around the world, and its uniform application is pursued by programs such as the UN/IDNDR Global Seismic Hazard Assessment Program.

During the past few years, the availability of records of individual paleo-earthquakes and of reliable indicators of the long-term activity of large active faults has provided key input to extend the historical record to cover recurrence times of 100 to 100000 years. These accomplishments (made possible by the results of new disciplines such as paleoseismology, geomorphology, geochronology, remote sensing and space geodesy) resulted in substantial improvements in the identification of seismic source regions adopted in traditional seismotectonic SHA, thus leading to novel approaches for more reliable hazard evaluation both in high- and low-seismicity areas and to the evaluation of non-stationary SHA in the few areas where the integration between the historical and geological record allows earthquake recurrence statistics to be constrained over long time periods (the SCEC experience for the Southern California area provides a clear example of integration of multidisciplinary datasets).

Starting in 1987 with a conference entitled «Directions in Paleoseismology» held in Albuquerque (New Mexico), the new science and the underlying scientific concepts have become the object of specialized meetings and publications. Further information can be found in the special USGS «redbook» published following that conference (U.S. Geological Survey Open-File Rep., 87-673); in the proceedings of the GSHAP meeting held in Rome, 1-3 June 1992 (*Annali di Geofisica*, vol. 36, n. 3-4); in the proceedings of the workshop on Paleoseismology held in Marshall, California, 18-22 September 1994 (U.S. Geological Survey Open-File Rep., 94-568); and in a special section of the *Journal of Geophysical Research* (Section B, vol. 101, 1996) entirely devoted to paleoseismological practice.

3. The 1995 Erice workshop

These fundamental issues were recently addressed during the conference *Active Faulting Studies for Seismic Hazard Assessment* organized within the International School on Solid Earth Geophysics, a series of yearly conferences held at the E. Majorana Centre for Scientific Culture (EMCSC) in Erice (Sicily) since 1984. The conference was planned and sponsored by the Istituto Nazionale di Geofisica of Rome, with additional support provided by the EMCSC, the World Laboratory of Lausanne, the International Lithosphere Program and UNESCO. The goal of the workshop was to provide a cross-national forum for reviewing recent advancements in studies of active faulting and related disciplines, for testing the extent to which the worldwide practice of seismic hazard assessment responds to such advancements, and for critically examining the current practice of seismic hazard assessment through the interaction among scientists, engineers and planners.

The Erice conference consisted of 35 invited presentations and panel-discussions with the participation of more than one hundred scientists from 25 countries. The activities were grouped in four main sessions:

- i) a global survey of active faulting observations and investigations in different regions and tectonic environments;
- ii) a presentation of the state-of-the-art and of the innovations of the disciplines that contribute to the assessment of the seismogenic potential of individual faults;
- iii) a discussion of methodological approaches and user requirements for the integration of the geological input into comprehensive models of seismic hazard;
- iv) a global survey of national and regional seismic hazard assessment programs, with special emphasis on the use of the geological input.

In Erice the importance of active fault characteristics was discussed in the context of seismotectonic probabilistic SHA and with the understanding that the meaning of the expression «active fault» and the relevance of specific fault characteristics may vary depending on the motivation of each study (*i.e.* to understand the geodynamics of a region or the physics of crustal faulting). The following ten recommendations and points of discussion focusing on active faulting studies for SHA summarize the consensus expressed by the meeting participants based on their own experience and results and on the ensuing discussions during and after the workshop.

In addition, with the goal of maximizing the impact of future active faulting studies on seismic hazard calculations, a scheme and a table are proposed in the Appendix, assigning comparative weights to different fault characteristics based on their direct impact on SHA.

4. Active faulting studies for SHA: ten points of discussion

- 1) *Definition of active fault* – An active fault of interest for SHA is a structure that has an established record of activity in the late Pleistocene (*i.e.* in the past 125 ka) and a demonstrable or inferable capability of generating major earthquakes. Other fields of tectonic research may conduct studies of active faults assigning different meaning and significance to their activity and characteristics.

2) *Importance of active faulting studies for SHA* – The recently acquired capability of identifying and parameterizing discrete rupture segments and individual Holocene earthquakes is shifting the emphasis of global SHA practice towards the use and standardization of the geological input. The promising results obtained during just a few years demand that such investigations be extended to as many active faults as possible in all tectonic domains, with particular regard to areas of moderate seismic activity.

3) *The establishment of a new science* – Paleoseismology is a new, rapidly developing science with applications so far restricted to few areas of the world. The diffusion of paleoseismological techniques and the routine acceptance and application of its results in the SHA practice require a coordinated effort to spread knowledge, established methodologies and results. The achievement of this goal should be encouraged through (i) the activities of international programs and commissions now focusing on neotectonic research (among these the INQUA Commission on Neotectonics of the International Association of Quaternary Studies, the IUGS, the ILP's Theme II programs: II-0 Global Seismic Hazard Assessment Program, II-2 World Map of Active Faults and II-3 Great Earthquakes of the late Holocene, several IGCP Projects, the ESC's), (ii) the organization of international training courses (*i.e.* those organized by the ILP's Theme II-3 or by UNESCO/GFZ), (iii) joint fieldwork, workshops and special sessions in international meetings, (iv) the wide dissemination and publication of results, (v) the establishment of criteria for the standardized identification and analysis of the paleoearthquake record, (vi) the compilation of standardized databases with accepted criteria for quality control and validation, and (vii) the close coordination with the end-users of paleoseismological data (*i.e.*, the SHA practitioners).

4) *Quality control and validation* – The development of criteria and procedures for scientific validation and quality control is a fundamental step to ensure the widespread diffusion and the confident use of active faulting data,

particularly of those concerning the paleoearthquake record. Possible ways include matching the historical record with geologically well documented and dated large earthquakes; establishing test areas for comparative studies; the peer review of ongoing field investigations; and the dissemination of the results in international journals.

5) *Databases* – The value of databases from all fields of paleoseismological research that can contribute to improved SHA is recognized and their continued upgrade, improvement, and standardization at global scale is encouraged. Databases should contain data reported in a manner that will be useful to other researchers whose needs were not anticipated, and should include both the direct results of the investigations and robust parameterizations of the seismic source from geological input with the associated uncertainties. This involves establishing suitable requirements to be met prior to the incorporation of new records in the database, which must include estimates of the uncertainty and completeness of the information in time and space. All databases should be open and readily accessible, and their existence and characteristics should be publicized in the geological, geophysical, and SHA communities.

6) *New approaches* – The further development of direct and indirect source identification and earthquake dating techniques should be continued and expanded. In recognition of the fact that conventional paleoseismic methodologies – which traditionally include logging and dating through geochronology buried surface ruptures associated with paleoearthquakes – cannot be applied in all seismotectonic settings, the development of new tools capable of identifying and parameterizing earthquakes of the recent and distant past – *e.g.* improving the dating of coastal marine fossils, characterizing blind faults through their long-term geomorphic expression, modeling marine terraces and other landscape features that offer quick response to active tectonics, investigating the spatial distribution and age of paleoliquefaction features, detecting traces of large paleoearthquakes in the archaeological record –

is crucial to increase the geographical coverage, the reliability and the precision of the geological input in the global practice of SHA.

7) *Coordination with SHA* – Despite recent advances in SHA methods and the growing acceptance of the paleoseismological input, there are still large communication gaps between geologists, seismologists, engineers and public officials devising building codes and seismic zonations. The international scientific community still seems ignorant of how their data are or could be used for SHA and how to put them in a form to ease their widespread acceptance. Conversely, all too often important datasets on active faults are not used or are introduced too late in the established SHA practice. In order for active faulting studies to have the highest impact on SHA, close integration must be maintained between the novel developments and the routine application of paleoseismological investigations in SHA programs. To this purpose active faulting studies should strive to provide parameters of direct input in SHA. Paleoseismicity experts should assume a direct role in SHA programs, while SHA methodologies should evolve to make full use of the geological input. A possible scheme weighing the characteristics of active faults based on their impact on SHA is presented in Appendix.

8) *Understanding the earthquake recurrence* – Since the ability to interpret a limited record of past earthquakes to project future hazard depends strongly on assumed regularity distributions, an important area of uncertainty in SHA is the regularity in time, space and size of earthquake recurrence. Due to lack of a more complete time history and of a clearer understanding of the mechanics of the seismogenic process, most seismic hazard studies assume some combination of segmentation, characteristic displacements in successive events, nearly uniform slip along segments, and time-predictable, slip-predictable or quasi-periodic earthquakes. By revealing the spatial and temporal patterns of the earthquake cycle, paleoseismological investigations can improve the present knowledge of the earthquake generation, which in turn will enhance our under-

standing of seismic hazard. Special emphasis should be put on fault systems for which detailed instrumental, geological or historical information is available in addition to the age and location of prehistoric earthquakes.

9) *Multidisciplinary source investigations* – Investigations of recent large earthquakes (Landers, Kobe) provide further evidence for heterogeneity of the timing history and slip distribution of the rupture process. Detailed paleoseismological investigations can help constrain the coherence of such complexity over repeated earthquakes and should be integrated with complementary studies (*i.e.* geodesy, modeling of broadband seismograms and strong-motion records) in multi-disciplinary investigations of source properties and mechanics, also with the goal of establishing to what extent and with what confidence each technique can be used to parameterize the earthquake source.

10) *Outstanding problems* – A host of questions remain, to which the study of paleoearthquakes will help provide an answer. Among these: what causes earthquake rupture to stop? How good are the regressions between moment and fault length for very large events? How do the fault length inferred before the earthquake and that measured after the earthquake compare? How does magnitude relate to fault length and segmentation in complex tectonic areas? Is there a wide observational basis for segmenting faults? What is the contribution of less prominent, second order faults to seismic hazard? What is the expected seismogenic behavior of faults in changing tectonic stress regimes?

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Appendix. Impact of characteristics of active faults on SHA.

The enclosed table presents a summary of specific fault characteristics and their importance for seismotectonic probabilistic seismic hazard. This table and the following discussion are intended to maximize the impact of future active faulting studies on seismic hazard calculations. For any given characteristic the rating reflects the expected influence on seismic hazard resulting from the combination of the intrinsic sensitivity of hazard computations to that characteristic and of the general level of epistemic uncertainty associated with it: small impact indicates that the range and uncertainty of the given fault characteristic will introduce a factor smaller than about five in the seismic hazard value (annual probability of ground shaking); large impact indicates a factor of five or more. It is recognized that the importance of these characteristics may be different for other types of active fault studies, *e.g.* to understand the tectonics of a region.

The first two characteristics in the table are different representations of the existence and activity of the fault. The first – the actual recognition that the fault is active – has a larger effect on hazard computation than the exact probability of activity of the fault in the current tectonic stress regime.

The issue of segmentation does not in itself influence on seismic hazard, other than through the assessment of the characteristic magnitude range and rate.

The magnitude model selected to characterize the earthquake recurrence has large importance. If an exponential model is used, the parameters (especially the rate of activity) are usually calibrated with historical seismicity. In plate margin regions, seismicity is usually sufficient to estimate the rate of activity, and the uncer-

Fault characteristic	Importance
Existence as an active feature	High
Probability of activity	Low
Location	Low
<i>LENGTH</i>	
– For site near fault	Low
– For site off end of fault	High
Depth of seismogenic zone	Low
Dip	Low
Sense of slip	Low
<i>MAGNITUDE MODEL</i>	
<i>– If exponential model:</i>	
– Rate of activity (plate margins)	Low
– Rate of activity (intraplate settings)	High
– <i>b</i> -value	Low
– Maximum magnitude	Low
<i>– If characteristic model:</i>	
– Slip rate or characteristic rate	High
– Characteristic magnitude range M_{CHAR}	High
– Temporal model (renewal, memory, cluster)	High
– Rate of occurrence of event in short term	High

tainties in b -value and maximum magnitude are not influential on seismic hazard. In intraplate settings or areas of low seismicity the uncertainty in rate is higher and may have a large influence on seismic hazard.

For the characteristic earthquake model the measure of activity rate (the slip rate or rate of occurrence of characteristic earthquakes) may be affected by a large uncertainty and may therefore strongly affect hazard. Also the range of the characteristic magnitude M_{CHAR} has a large importance; in particular the lower value of M_{CHAR} is often critical because, for a fixed slip rate, it governs the highest rate of occurrence and the highest seismic hazard. The preferred temporal model of occurrence of characteristic earthquakes also has a large importance; the inclusion of a cluster model, for example, may greatly affect the rate of occurrence in the decades following a large event.

Not all characteristics of active faults are shown in the table; parameters which influence characteristics already listed are not included. For example, the time since the last earthquake is not designated as a separate characteristic, as it governs the large importance assigned to the rate of occurrence of an event in the short term.
